Development of a dichroic beam splitter for Subaru AO188

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ABSTRACT

We have developed a dichroic beam splitter for the Subaru AO188, which reflects optical light (0.4-0.9 μm) for wavefront sensing and transmits near-infrared light (0.93-5.2 μm) for science observations. The beam splitter is made of 145mm $\times$ 200mm calcium fluoride substrate coated by fluoride and metal chalcogen compound multilayer, which should be a best way to realize high transmittance over wide wavelength range in the near infrared. However, since typical fluoride soft coating is less resistant to the moisture in the air, the fluoride coating become damaged as we use on the AO188 optical bench which is placed in the room temperature condition. We have performed several accelerated endurance tests of the beam splitter under high-humidity condition by changing the design of the coatings, and found an optimal solution with an oxide protection layer which prevents the damage of the dichroic coating and keeps high transmittance at near-infrared wavelength. In this paper, we report the results of the endurance tests and the performance of our dichroic beam splitter.

Keywords: adaptive optics, beam splitter, thin film coating

1. INTRODUCTION

We are developing a new curvature adaptive optics (AO) system with 188 elements for the Subaru telescope which is capable of both natural guide star (NGS) and laser guide star (LGS) modes.[1] The science instrument mainly working with the AO188 is the InfraRed Camera and Spectrograph (IRCS), which is designed to perform observations in 0.93−5.2 μm wavelength.[2] Among the several modules for the AO188 system, one of the key components is a dichroic beam splitter. In the AO188 system, since the wavefront sensor (WFS) measures the disturbance in visible wavelength, the dichroic beam splitter is essential for splitting the light into visible for wavefront sensing and near-infrared for science observations. Fig1 shows the optical layout of the AO188 system.[3] Two dichroic beam splitters, called BS1 and BS2, are placed in the f/13.9 convergent light path. The BS1 reflects the visible light for the WFS and transmits the near-infrared light for the IRCS. The BS2 reflects the light from a LGS (∼589nm) for high-order WFS and transmits the rest of visible for low-order WFS.

In this paper, we describe about the development of the BS1 coating and report the results of the endurance tests and the performance of the BS1 coatings.

2. SPECIFICATIONS

2.1 Substrate

The substrate of the BS1 is made from calcium fluoride (CaF_2) to transmit near-infrared light up to 5.2 μm. Since the beam splitter is placed in the convergent light path at a tilt angle of 45 degrees, we use a wedged plate for the substrate to minimize the effect of astigmatism. The size of the substrate is 145 mm $\times$ 200 mm, 20mm in thickness, and the vertex angle is 0.196 degree. We cut the four corners of the substrate and the resultant shape of the substrate is octagonal. The measured reflected and transmitted wavefront errors through the substrate are $1/4\lambda$ PV and $1/7\lambda$ PV, respectively, over any 60 mm diameter circle which roughly correspond to a beam size at the surface of the BS1.

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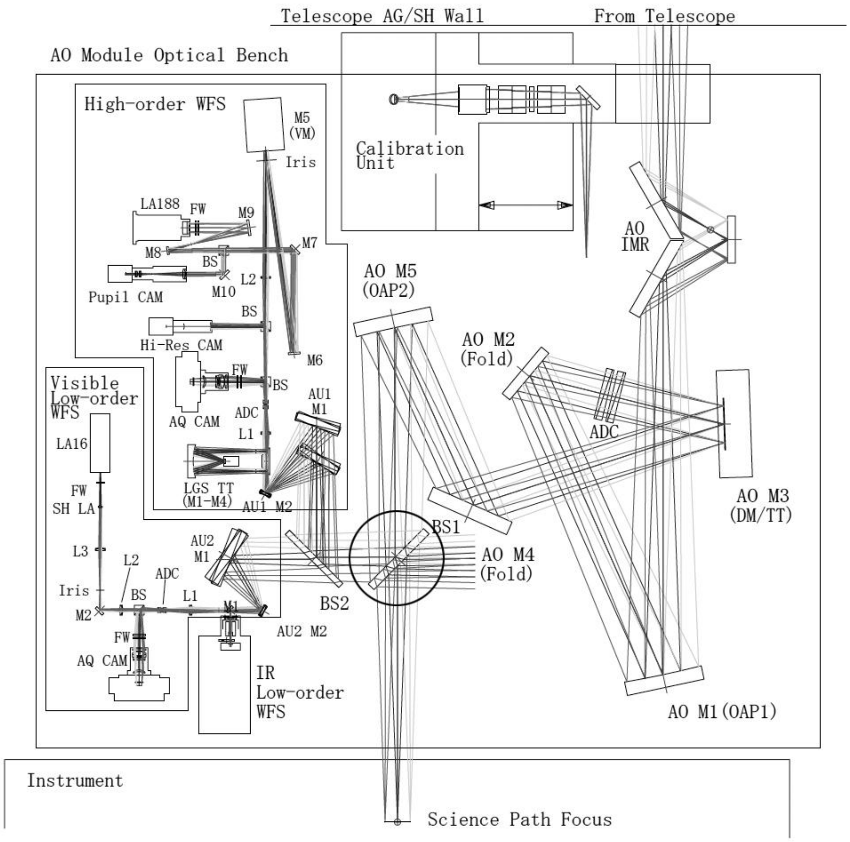

Figure 1. Optical layout of the AO188 system. The BS1 is locate around the center of the AO188 optical bench (encircled area).

2.2 Spectroscopic property

In Table 1, we summarize the required specification of the coating. Since we use the light from 0.93 μm to 5.2 μm for science observations with the IRCS, we set the cut-off wavelength of the dichroic coating at 0.9 μm. We request more than 90% transmittance at z and J-bands and more than 92% transmittance at H, K, L, and M bands. As for the visible reflectance, we request the average reflectance of more than 99% at the range from 0.45 μm to 0.85 μm where the photon efficiency of the avalanche photo diode, which is the detector in the WFS, is more than 50%.

Table 1. Required specifications of the dichroic coating.

Beam incident angle	45 degrees
Transmittance	
$0.45 - 0.84$ μm	$< 1\%$
0.90 μm	$> 50\%$
$0.93 - 1.33$ μm	$> 90\%$
$1.48 - 1.78$ μm	$> 92\%$
$1.95 - 2.50$ μm	$> 92\%$
$2.50 - 5.20$ μm	$> 92\%$

3. COATING

The dichroic coating was manufactured by Optical Coatings Japan Co., Ltd.. To minimize the effect of the stress in a thin film coating, the dichroic coating was performed by a soft coating method. To realize high transmittance over wide wavelength range in the near infrared up to 5.2 μm, the dichroic coating is designed to use fluoride (low index) and metal chalcogen compound (high index) multilayer with thickness about 3 μm. Among the fluoride materials, thorium fluoride is the currently preferred material whose evaporated film is durable and chemically stable and exhibit low stress. In fact, we developed a similar beam splitter for our old AO36 system[4] using thorium fluoride as a coating material. Recently, however, use of thorium fluoride becomes almost impossible due to its radioactivity and new state and/or federal regulations for disposal of radioactive materials. Therefore, we have to use the other fluoride material for our new beam splitter to substitute thorium fluoride which can provide similar properties. However, the thin film of the fluoride materials other than thorium fluoride is not durable in ambient condition. Typical fluoride thin film adsorbs the moisture in the air and then the coating can easily become damaged or detach from the substrate as time goes by. To test the long-term durability of the coating and find an optimal solution of the coating, we manufactured several types of the coating on small CaF_2 substrates and conducted the accelerated endurance tests using an endurance test chamber.

4. ENDURANCE TESTS

First of all, we checked the short-term durability of the dichroic coating, by putting the test pieces in the ambient condition in the laboratory and the dome for about three weeks and confirmed that the coating of the test pieces were not damaged and the transmittance of the coating were not changed for both conditions.

To determine the environment condition of the accelerated endurance tests, we monitored the temperature and relative humidity of the laboratory at the Subaru base office and the dome of the Subaru telescope where the AO188 system is mostly placed. Figure 2 shows the frequent distribution of the temperature (T) and relative humidity (RH) at the base laboratory and the telescope dome. We found that the environmental condition in the base laboratory is very stable at a temperature of 22−24 °C and at a humidity of 42−48 %, while the condition in the telescope dome is distributed within wider temperature and humidity ranges of -5−10 °C and 0−80 %, respectively. Following the results of the environment monitor, we decided to perform the accelerated endurance tests under (1) T=20 °C, RH=60% and (2) T=10 °C, RH=80 % for simulating the worst case in the laboratory and the dome, respectively.

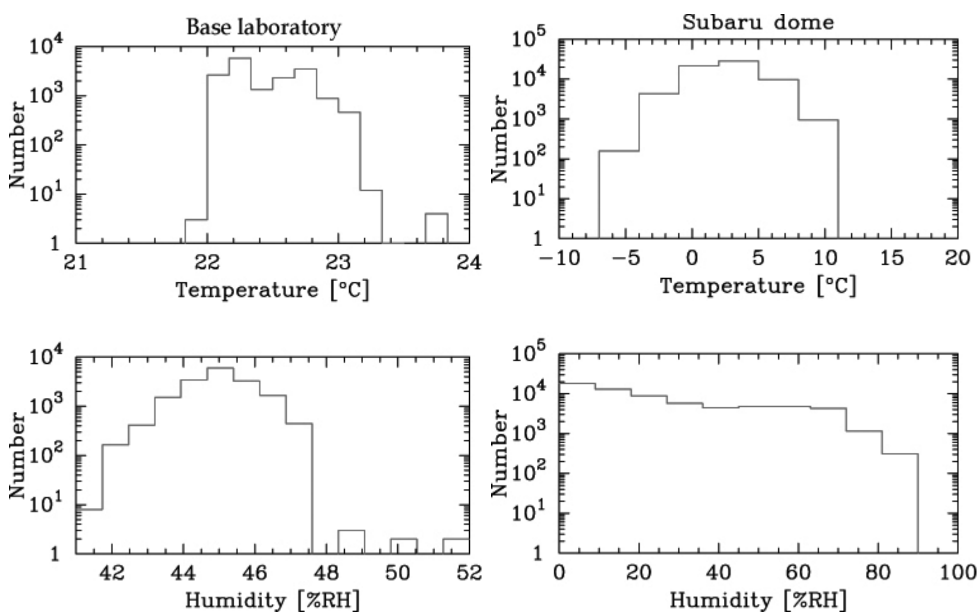

Figure 2. Frequent distribution of the temperature and relative humidity at the base laboratory and telescope dome.

Figure 3 shows the images of the test pieces of the dichroic coating before and after the accelerated endurance tests under the laboratory (1) and dome (2) conditions. The dichroic coating was apparently not damaged with 6 days in the laboratory condition, while the edge of the dichroic coating was damaged with 3 days in the dome condition. Although the relative humidity is higher in the dome condition (80 %) than in the laboratory condition (60 %), the absolute water vapor content in the dome condition ($\rho_w \sim 7.5$ g/m^3) is less than that in the laboratory condition ($\rho_w \sim 10.4$ g/m^3). This implies that the relative humidity is more sensitive for the damage of the coating than the absolute water vapor content. Therefore, we used only the dome condition in further accelerated endurance tests.

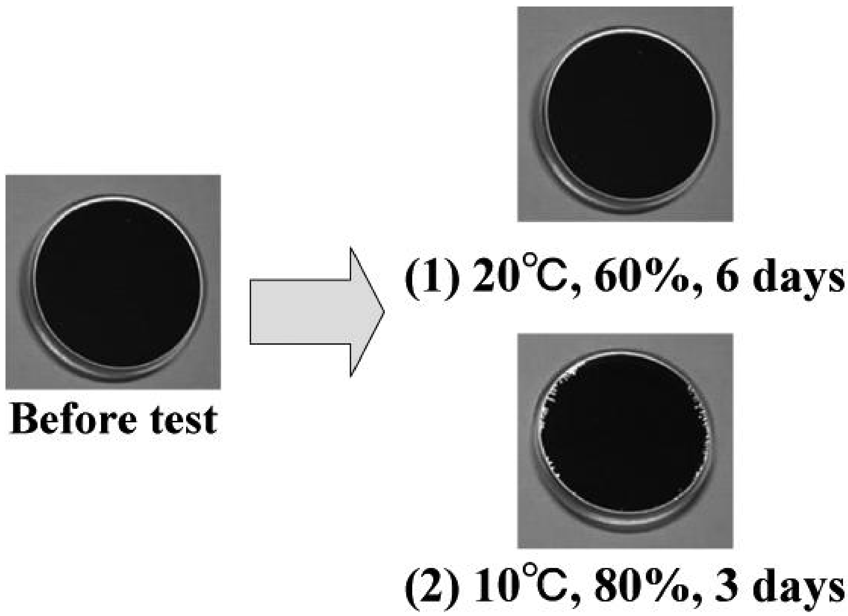

Figure 3. Results of the accelerated endurance test for the dichroic coating under the laboratory (1) and dome (2) conditions. The damage was appeared at the edge of the coating after 3 days in the dome condition (2).

To increase the durability of the coating, we performed a protection overcoat on the dichroic layers using an oxide material. According to the results of the previous endurance tests, we found that the damage appears from the edge of the coating. To protect the edge of the coating, the area of the overcoat layer is slightly larger than that of the dichroic layers (see Figure 4). However, thicker overcoat can decrease the NIR transmittance. We found from a simulation that the overcoat with a thickness less than 1.0 μm should satisfy the transmittance requirement for the BS1 (Table 1). Decrease of the NIR transmittance due to the overcoat with less than 1.0 μm should be $1 - 3$ %. We manufactured the test pieces with 0.3 μm and 1.0 μm overcoat and performed the accelerated endurance test under the dome condition.

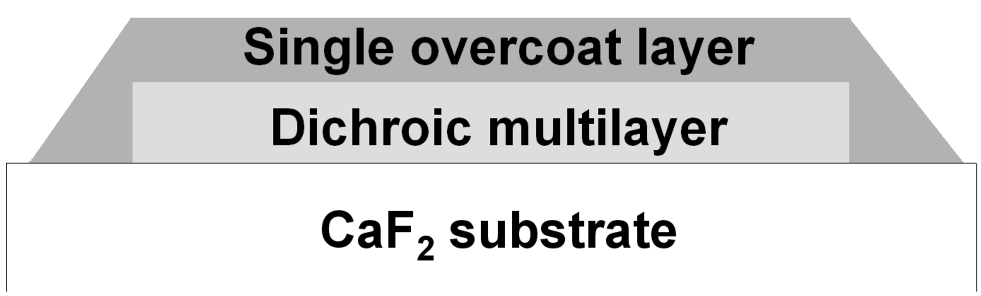

Figure 4. Schematic view of the coating layers on the CaF_2 substrate.

After 15 days, we found an 1 mm blister due to water penetration and some $\phi = 0.2$ mm cracks in the 0.3 μm overcoat piece at the edge of the dichroic coat (Figure 5). We also found that entire surface of the 0.3 μm one become dim. This might be due to water penetration into pinholes on the surface of the overcoat. On the other hand, we also found a smaller blister at the edge of the 1.0 μm overcoat piece, but no crack and dimming. The small blister in the edge of the 1.0 μm one seems not to be changed between 15 days and 50 days. We therefore concluded that the 1.0 μm overcoat on the dichroic coating is the best way to realize both high durability and high transmittance at NIR (0.9−5.2 μm).

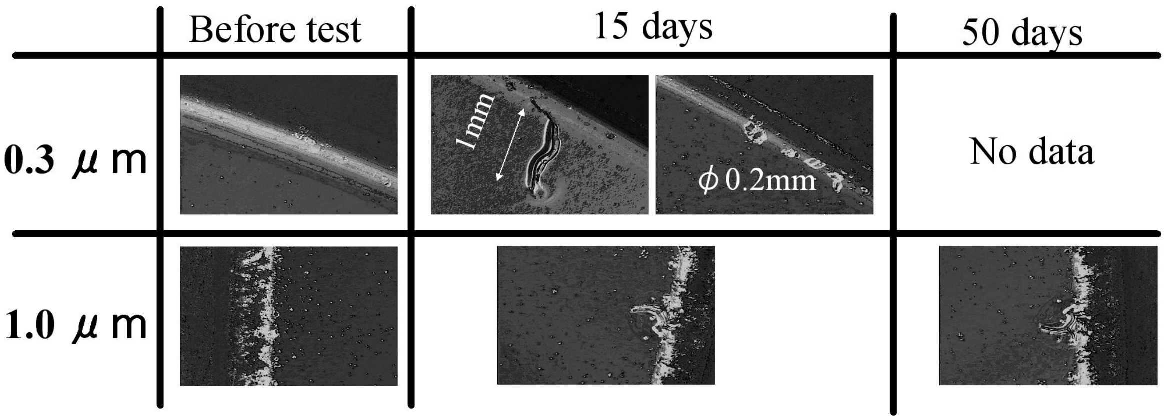

Figure 5. Results of the accelerated endurance test for the dichroic coating with a 0.3 μm and 1.0 μm protection overcoat under the dome condition (10 °C, 80 %). The edges of the dichroic coating are shown in all images. Blister and cracks were appeared at the edge of 0.3 μm one after 15 days test. A small blister was also appeared on the 1.0 μm one after 15 days, but it was not apparently changed during the subsequent test up to 50 days.

5. PERFORMANCE

Following the results of the endurance tests, we performed the coating of the BS1 consisted of the fluoride dichroic layers and the 1.0 μm oxide overcoat layer on the front surface of the BS1 substrate (see Figure 6). Figure 7 shows the resultant transmission curve for the BS1 compared with that for the old beam splitter for the AO36+IRCS. We confirmed that the measured transmittance of the BS1 satisfies the requirement listed in Table 1 and comparable to the transmittance of the old beam splitter for the AO36+IRCS that uses the thorium fluoride material.

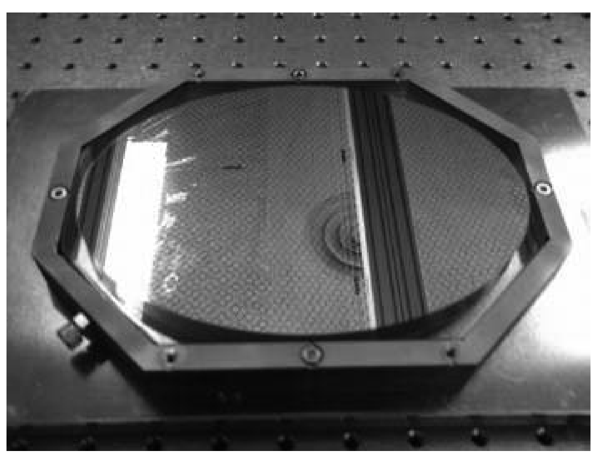

Figure 6. A picture of the dichroic beam splitter BS1. The dichroic coating and protection overcoat was performed on the front surface of the CaF_2 substrate. There is no coating on the back surface of the substrate.

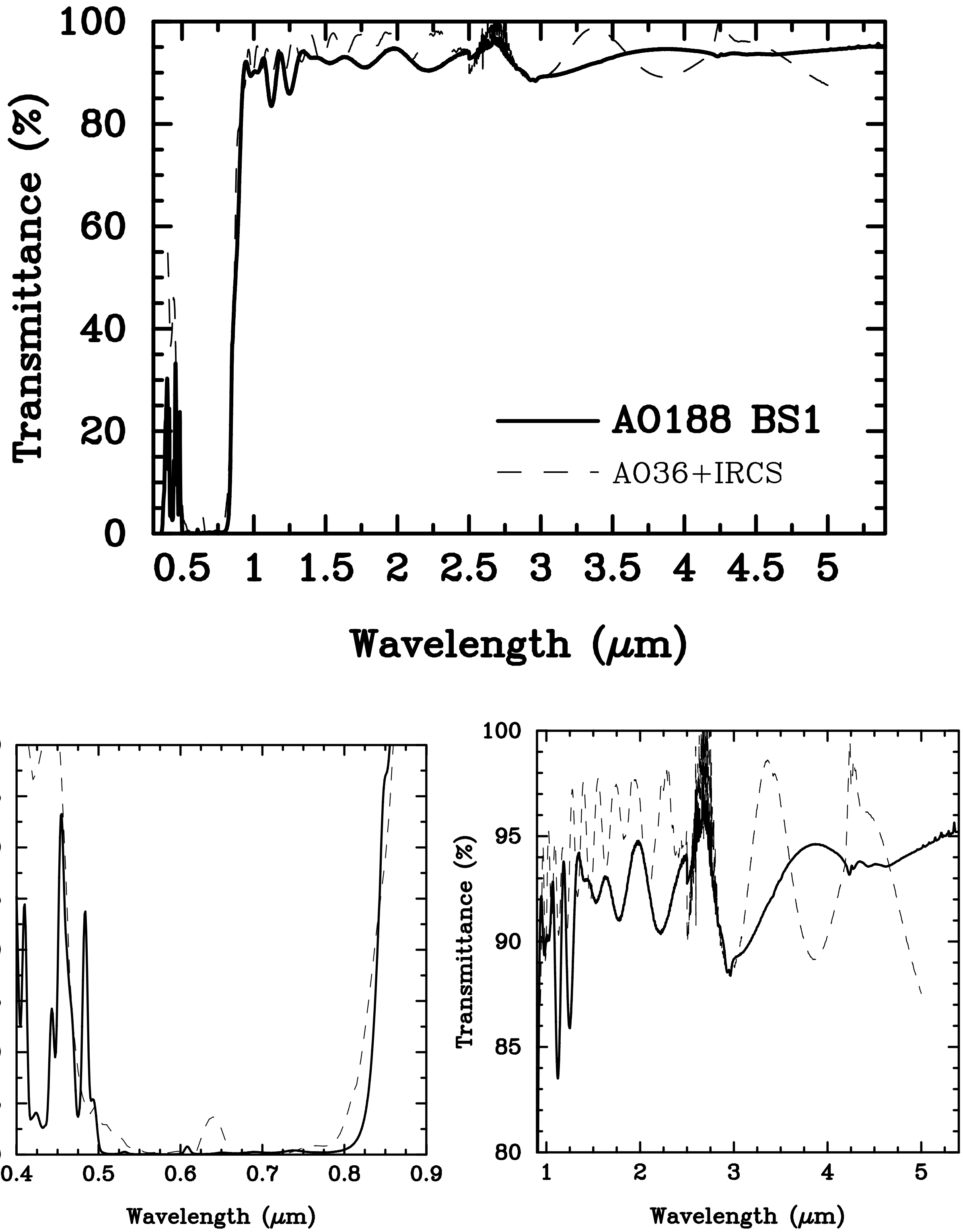

Figure 7. Transmission curve for the dichroic beam splitter BS1 in the AO188 system (solid line), compared with that for the old beam splitter for the AO36+IRCS (dashed line). The transmittance of the BS1 is almost comparable to the old one with fewer ripples at the NIR.

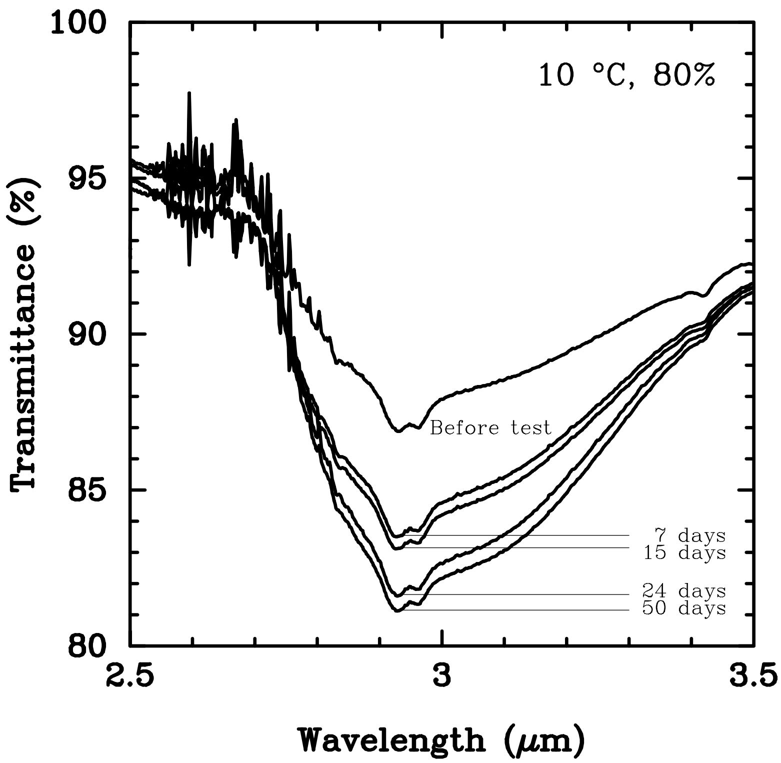

Figure 8. The water absorption feature around 3 μm. The depth of the absorption feature increases with time and would be saturated around the transmittance of 81 % at the bottom after 24 days under T = 10 °C, RH = 80 % condition.

It should be noted that water absorption feature at 3.0 μm was appeared after several days under the dome condition (10 °C, 80 %). The growth of the absorption feature was very slow (not vary from hour to hour) and stopped around the bottom transmittance of 81 % after 24 days under the dome condition (see Figure 8). The absorption feature seems not to be reversible once it appeared even if we put the test piece back to the dry condition area (10 °C, 0 %) for several days. To minimize this absorption feature, we have to keep the humidity around the BS1 as low as possible.

6. SUMMARY

We have manufactured a dichroic beam splitter for the Subaru AO188 system that reflects visible light and transmits NIR light using fluoride and metal chalcogen compound multilayer. To check the durability of the coating, we performed the accelerated endurance test under several conditions and found that the relative humidity is most sensitive to the damage of the coating. According to the results of the endurance test, we found an optimal solution of the dichroic coating with an 1.0 μm oxide protection overcoat which realize both high durability and high transmittance at NIR (0.9−5.2 μm).

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